

**Modelling Service Life and Life-Cycle Cost of
Steel-Reinforced Concrete**

**Report from the NIST/ACI/ASTM Workshop held in
Gaithersburg, MD on November 9-10, 1998**

Geoffrey Frohnsdorff

Building and Fire Research Laboratory
Gaithersburg, Maryland 20899



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William M. Daley, *Secretary*

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Nernst-Planck / Poisson set of equations. The diffusion of all ionic species present in the system can be accounted for by the model. It also accounts for chemical activity effects.

The transport of water by capillary suction is described by a diffusion-type equation, and the variation of the water diffusion coefficient is described by an exponential equation. The water content of the solid serves as the state variable for this part of the model.

Chemical reactions are modeled through a series of sink and source terms. The non-linear nature of each chemical reaction process is accounted for by a number of interaction isotherms. The influence of on-going chemical reactions on the material transport properties is accounted for. The effects of the chemically-induced alterations are described in terms of porosity variations.

To solve such a complex system of non-linear equations, a numerical algorithm must be used. All the equations are solved simultaneously. The spatial discretization of this coupled system is performed through the finite element method using the standard Galerkin procedure. An Euler implicit scheme is used to discretize the transient part of the model. The non-linear set of equations is solved with the Newton-Raphson algorithm. The second order algorithm gives a good convergence rate and is robust enough to handle the electrical coupling between the ionic flux and the water movement.

The model can be used to follow any changes in the concrete pore solution chemistry to obtain a precise description of the materials solid phase distribution. The model has been successfully applied to cases of degradation by sulfates and by chlorides.

2.7 THE DURAMODEL® FOR THE DESIGN OF COST-EFFECTIVE CONCRETE STRUCTURES

Paul Tournay, W.R. Grace Company

Systems for the corrosion protection of reinforcing steel in concrete have three possible effects: 1) reduction of the ingress of chloride, 2) increase of the chloride level at which corrosion initiates; and 3) reduction of the corrosion rate once corrosion initiates. The performance of a protection system needs to be evaluated in light of these effects. Once these are documented, one can determine the initial costs of the protection system and then project the time to corrosion for first and subsequent repairs. The future repair costs are converted to present day costs using a net present value analysis. Examples have shown that eliminating corrosion protection at the design stage is an expensive long-term option.

The Grace model [19] describes each of the three possible effects mathematically. The model is WINDOWS-based and the inputs include the type of structure and application, and the exposure conditions – temperature, surface chloride, thickness, chloride build up/year, and the corrosion threshold. Outputs include the service life with repair and the costs for various protective systems. Evaluation of the performance of a protection system as related to the three effects requires data from accelerated and long-term field and laboratory tests, and the evaluation requires an understanding of corrosion mechanisms as well as protection mechanisms; the same accelerated testing techniques cannot be used for all methods.

Since many protection systems affect the rate of diffusion or the chloride levels needed for corrosion, the prediction of chloride ingress is critical for life-cycle analyses. The exact rate of chloride diffusion through concrete cannot be calculated due to the heterogeneous nature of concrete and the differences between concreting materials. However, an approximate value can be obtained with sufficient accuracy for estimating the ingress of chloride into concrete structures in the field as a function of exposure conditions.

Fick's second law of diffusion can be used to calculate an effective diffusion coefficient, D_{eff} , if the chloride concentration at any time is known as a function of depth. A more rigorous approach would determine chloride binding and calculate the diffusion coefficient independent of chloride binding. To minimize effects of sorption, longer test periods are also recommended. However, work in the Grace laboratory and by others has shown that the effective diffusion coefficient can be used to predict chloride profiles, when it is determined after at least one or two years of exposure, since this exposure allows opportunity for both sorption and diffusion processes to occur. Hence, D_{eff} takes account of mechanisms other than pure diffusion. Diffusion coefficients and surface concentrations are determined by solving the equation from Fick's second law. Solutions for this equation, $\partial c / \partial t = \nabla^2 c(t)$, are given in the model for: a) a semi-infinite slab – applicable to cases in which the chloride ingress is from one side only, such as walls or decks under severe marine exposures, or submerged walls or slabs subject to constant chloride exposure, and b) cases in which chloride ingress is two-dimensional and chloride diffuses into the concrete from two sides, such as a square concrete pile.

Chloride concentration profiles from numerous laboratory and field studies have shown that a typical chloride diffusion coefficient for quality concrete is about $2 \times 10^{-12} \text{ m}^2/\text{s}$, but may be an order of magnitude higher for a low-quality concrete, and be significantly lower for quality concretes containing supplementary cementitious materials. Diffusion coefficients can be adjusted for different environmental temperatures.

To develop a chloride profile, it is necessary to know the surface concentration. Typical values for the surface concentration are 18 kg/m^3 for severe marine environments in the splash/tidal zone. When bridge decks are exposed to deicing salts, chlorides build up at a rate of about 0.6 kg/m^3 per year until about 14 kg/m^3 is reached and further increase stops due to surface saturation and the washing effect of rain.

From typical values noted in the SHRP program [20], it appears that corrosion damage needing repairs tends to occur five years after initiation of corrosion. However, when epoxy-coated rebar is used for both top and bottom mats of steel, the time to repair is estimated to be 20 years after corrosion initiation; (more research is needed to better define this value). Assuming that there is no increase in chloride threshold values for epoxy-coated rebar, the 20-year value reflects a 75% reduction in the corrosion rate. Corrosion inhibitors result in an increase in the chloride threshold value.

Life cycle cost analysis – Life-cycle costs of corrosion protection scenarios were examined [19]. For the bridge deck example, the costs did not include extra expenses associated with the handling of epoxy-coated rebar and traffic control; user delay costs and other loss-of-use

costs should also be included in the analyses. If these costs were included, only systems without repairs would make economical sense.

2.8 CREATING A STANDARD CORROSION SERVICE LIFE PREDICTION METHOD

Matthew A. Miltenberger, Master Builders Inc., Cleveland, Ohio

In order to model chloride diffusion, it is necessary to select appropriate boundary conditions and to have the necessary input parameters. The input parameters are the effective diffusion coefficient, the chloride loading, the depth of cover over the reinforcement and, perhaps, a temperature correction. Insight into the boundary conditions can be obtained by studies of buildup of chlorides at the concrete surface and by ponding experiments. Solutions to Fick's second law have been obtained for cases of buildup and constant chloride content.

In research at Master Builders, a chloride flux test cell, a chloride migration test cell, and ponding experiments have been used in the determination of diffusion coefficients for concretes with and without silica fume. (With the chloride flux test cell, it takes two to three years to obtain data for high-performance concrete.) For conductivity measurements in the migration test cell, the specimens were saturated with chloride solution prior to making the measurements. Plots of measured versus predicted diffusion coefficients showed reasonably good agreement. Among the comparisons made were: a) typical ponding test results -- chloride content vs. depth from surface (measured and Fick's 2nd law); b) complete chloride profile -- chloride content vs. depth from surface (measured and Fick's 2nd law); c) combined transport mechanisms -- chloride content vs. depth from surface (measured and Fick's 2nd law using D from flux test).

Standardization issues -- The standardization of a model, or models, for service life prediction will be a complex problem. Among matters that need to be addressed are: a) establishment of a common terminology, b) definition of calculation procedures, c) identification of applicable transport mechanisms, d) standardization of test methods, and e) provide guidance to all who need it. Ultimately the standard, or standards, to be drafted should help designers.

Standardization of terminology is important for improving communication and reducing confusion and, in this connection, units of measurement should be standardized and not left as they are, e.g., m²/s, cm²/s, mm²/yr, in²/yr.

As for the model calculations, among the issues are:

- Should the L-R (Load-Resistance) format be adopted?
- Should a model incorporate reduction factors to account for other distresses (e.g., cracking)?
- Should corrosion propagation be included?
- Should equation(s) for multiple chloride transportation modes be included?
- How should the model(s) be validated?